

PRECISION MEASUREMENT OF THE HIGGS BOSON MASS AND SEARCH FOR
DILEPTON MASS RESONANCES IN $H \rightarrow 4\ell$ DECAYS USING THE CMS DETECTOR AT
THE LHC

By

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I dedicate this to Jacob Myhre.

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Without so many two-legged blessings along the way, I could never have made it to this point in my academic career. Thus, I give my unlimited thanks to the following people.

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TABLE OF CONTENTS

	<u>page</u>
ACKNOWLEDGEMENTS	4
LIST OF TABLES.....	6
LIST OF FIGURES.....	8
CHAPTER	
1 INTRODUCTION	10
2 THE CMS DETECTOR.....	11
2.1 The Silicon Tracker	14
2.1.1 The Pixel Detector.....	14
2.1.2 The Strip Detector	16
2.2 The Calorimeters	16
2.2.1 Electromagnetic Calorimeter.....	16
2.2.2 Hadron Calorimeter.....	19
2.3 The Solenoid and the Steel Return Yoke.....	21
2.4 The Muon System	23
2.4.1 Let Me See These CSCs	24
2.4.2 Drift Tube Chambers.....	28
2.4.3 Cathode Strip Chambers	28
2.4.4 Resistive Plate Chambers.....	28
3 SUMMARY	29

LIST OF TABLES

Tables

page

LIST OF FIGURES

<u>Figures</u>	<u>page</u>
2-1 Life-size poster of the CMS detector, taken during CERN Open Days 2019 in the SX5 warehouse where parts of CMS were assembled.	11
2-2 Points 1 through 8 along the LHC. Collisions occur at Points 1 (ATLAS), 2 (ALICE), 5 (CMS), and 8 (LHCb), whereas the remaining points are used for LHC beam maintenance and testing.	12
2-3 Cut out of the CMS detector showing its various subdetector components.	13
2-4 A transverse view of CMS showing the “filtration process” as different particles pass through different subdetectors. A positron (solid red line) curves due to the presence of the magnetic field and gets stopped in the ECAL, creating an EM shower. A photon (blue dashed line) does not get detected at all by the Silicon Tracker, since it has no electric charge. It continues through to the ECAL and makes a shower here, like the positron. Charged hadrons (solid green line) will show curved tracks from the Silicon Tracker, may leave some trace in the ECAL, but primarily get stopped by the HCAL creating hadronic showers. Neutral hadrons (dashed green line) do not interact with the tracker, and only undergo EM showers a little in the ECAL, but show most energy deposits in the HCAL. Muons (solid blue line) are detected by the Silicon Tracker and then mostly pass through the other subdetectors without interacting until they finally reach the Muon System. Using the Lorentz force law and knowing which direction the magnetic field is pointing, one can deduce the sign of the charge of the particle. Based on the radius of curvature from the trajectory, one can then calculate the momentum and energy of the particle.	15
2-5 (Left) A simulation of the silicon tracker, showing the 3 cylindrical layers of the pixel detector (pink), 4 layers of the TIB (green), and the 6 layers of the TOB (blue) of the strip detector. The endcap components are also shown. (Right) A picture of the real silicon tracker at the center of CMS.	16
2-6 A transverse view of the silicon pixel and strip detectors, explicitly labelling the different layers involved.	17
2-7 (Left) Cross sectional view of the electromagnetic calorimeter of CMS. (Right) One of the Dees which comprise the EE. Each square of 5×5 crystals constitutes a “supercrystal”. Figure taken from Ref.REFERENCE JINST.....	18
2-8 (Left) ECAL crystals made from PbWO ₄ are grown in a lab. (Right) Although made mostly of metal, ECAL crystals are transparent and have a photomultiplier detector attached at the end.....	18
2-9 A cross-sectional quadrant of CMS showing the locations of the HCAL components: the barrel (HB), outer (HO), endcap (HE), and forward (HF) detectors.	21
2-10 A longitudinal cross section of CMS showing the values of the magnetic field over the volume of CMS and various field lines. The magnetic field reaches its maximum of 3.8 T in the center of the detector.	22

2-11 (Left) A cut out view of the ME+ endcap, simulated. Also shown is the coordinate system that CMS uses. (Right) The actual ME-2 disk is shown, revealing its ME-2/1 and ME-2/2 rings of CSCs.	24
2-12 (Left) A CSC with its top layer exposed. You can see very thin gold-plated tungsten wires which actually span the entire width of the CSC. Thicker vertical strips run along the length. (Right) More detail showing the radial strips and the horizontal wires. Also shown is the 5 segments of a CSC.	25
2-13 Longitudinal cross section of CMS, showing the different pseudorapidity values (η) and also the different subdetector regions.	26
2-14 A muon passes through one of the gaseous layers of the CSC, ionizing the gas mixture and inducing a charge on the wires and strips.	27
2-15 (Left) Comparators are used to compare neighboring strip cluster charge to determine on which half-strip the peak charge resided. (Right) A muon passes through all six layers of a CSC inducing charge on various half-strips.	28

CHAPTER 1 INTRODUCTION

The universe, while overwhelmingly vast, is comprised of a curiously small number of elementary particles. These particles and their strong, weak, and electromagnetic interactions with each other are accurately described by the Standard Model (SM). A major shortcoming of the SM was its inability to predict the masses of these particles.

This dissertation presents a precision measurement of the Higgs boson mass and using LHC proton-proton collision data from Run 2 data set from

The SM was not able to predict the masses of these particles until 1964 when the Brout-Englert-Higgs mechanism suggested that It wasn't until 1964 that the Brout-Englert-Higgs mechanism gave a self-consistent way to : by breaking the electroweak gauge symmetry of the vacuum would give rise to non-zero masses of the weak gauge bosons. This would yield a secondary effect too: there should exist a fundamental scalar boson which is the quantum of the so-called “Higgs field”. On July 4th, 2012, this Higgs boson was discovered.

At first glance, the universe appears to be an overwhelmingly vast and complicated place. However upon closer inspection, it is comprised of only a few different kinds of fundamental particles. Particle physics has given rise to the Standard Model (SM) which mathematically describes these constituents and their interactions with each other.

The Standard Model (SM) is an impressively accurate mathematical theory which describes the fundamental particles of the universe and the rules for their possible interactions. Problematically though, the SM predicts that all particles are massless.

Get to the Higgs boson.

Why is it important? Knowing the mass of the Higgs boson

CHAPTER 2

THE CMS DETECTOR



Figure 2-1. Life-size poster of the CMS detector, taken during CERN Open Days 2019 in the SX5 warehouse where parts of CMS were assembled.

Weighing in at 14,000 tonnes, standing 5 stories tall (15 m), and reaching 29 m long, the Compact Muon Solenoid (CMS) experiment is one of two general-purpose particle detectors at the LHC (Fig. 2-1). CMS is situated approximately 100 m under the earth at the fifth collision point (Point 5) along the LHC (Fig. 2-2). In 2012, both CMS and its competing experiment, ATLAS, independently discovered the Higgs boson.

As discussed in Section (TODO: REF), the LHC collides bunches of protons every 25 ns to produce thousands of new particles which then travel away from the interaction point. CMS is built around the interaction point in a series of cylindrical subdetectors for nearly hermetic coverage so that most of the particles must travel through CMS. The detector sports a solenoid, after which CMS was named, which generates a 3.8 T uniform magnetic field that points longitudinally down the central axis of CMS. This strong magnetic field applies a Lorentz force on the outgoing charged particles, causing them to follow helical, momentum-dependent trajectories. These curved tracks are then better separated from one another which assists in particle identification. Neutral particles experience no Lorentz force and thus travel in straight lines.

The subdetectors measure the properties of the outgoing particles and carefully filter them out in a clever way (Fig. 2-3). Particles interact with the subdetectors, leaving so called “hits” where

they passed through. Hits are reconstructed into tracks. From the track curvature, deduce charge and momentum of the particles. Depending on which subdetector (or combination of subdetectors) was hit by the outgoing particles, the type of particle can be deduced. A few example particles

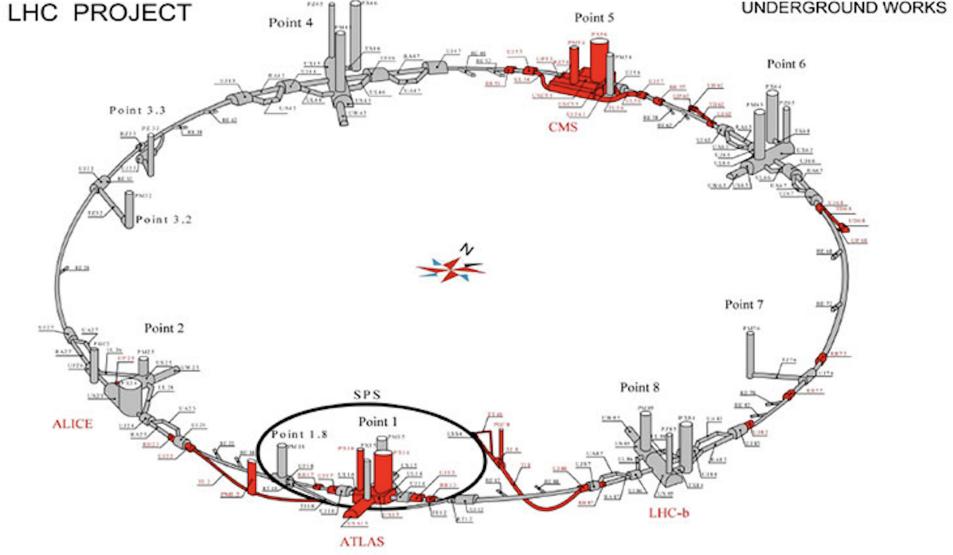


Figure 2-2. Points 1 through 8 along the LHC. Collisions occur at Points 1 (ATLAS), 2 (ALICE), 5 (CMS), and 8 (LHCb), whereas the remaining points are used for LHC beam maintenance and testing.

and their associated tracks are shown in Fig. 2-4.

Before discussing each subdetector in the following sections, it is useful to define the coordinate system used in CMS: a typical, right-handed, three-dimensional Cartesian coordinate system (x, y, z) is used, whose center $(0, 0, 0)$ is placed at the nominal pp collision point within CMS. The x -axis points towards the center of the LHC, the y -axis points vertically upward, and the z -axis points westward towards the Jura mountains, tangential to the beam direction. Since CMS covers almost the entire spherical 4π steradians around the interaction point, it is convenient to use spherical coordinates (r, ϕ, θ) , in which r measures the radial distance in the x - y plane, ϕ measures the azimuthal angle in the x - y plane as measured from the x -axis, and θ measures the polar angle as measured from the z -axis. When dealing with ultra-relativistic particles like those produced at the LHC, special relativistic effects like length contraction must be taken into account and so the coordinate θ becomes frame-dependent. It is thus helpful to convert θ to the Lorentz-invariant

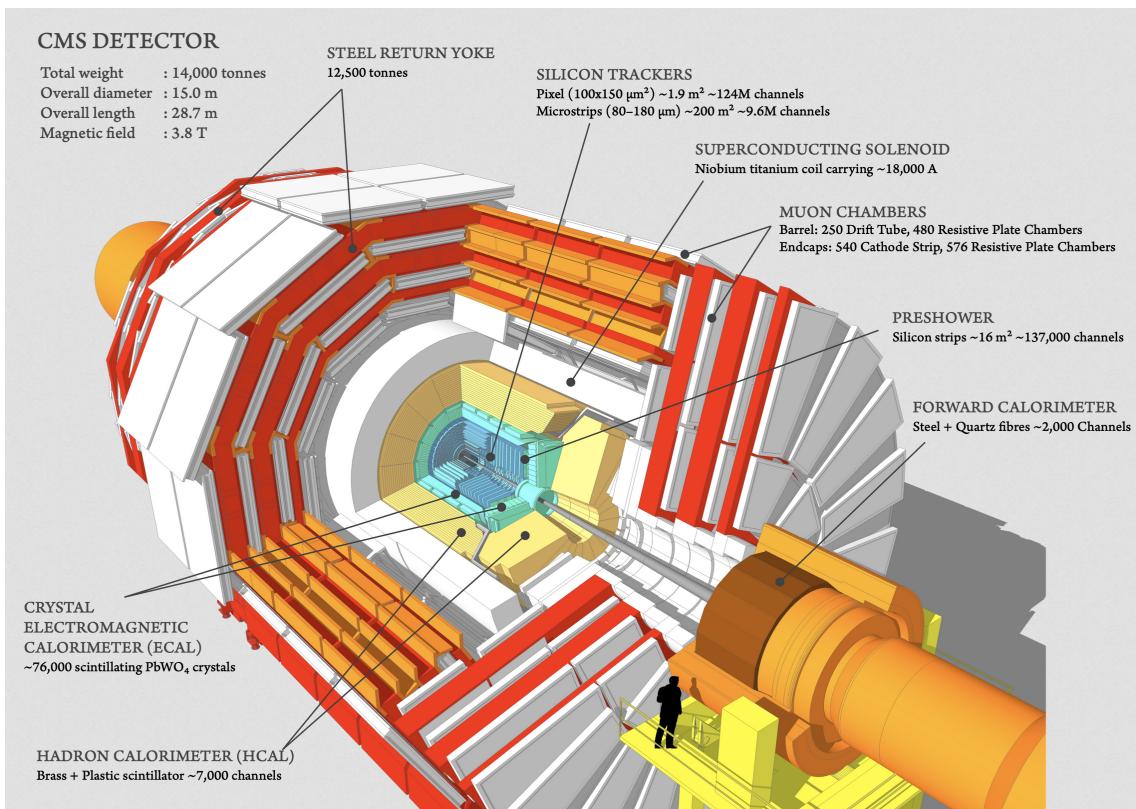


Figure 2-3. Cut out of the CMS detector showing its various subdetector components.

quantity called pseudorapidity (η), which is defined as:

$$\eta = -\ln(\tan(\theta/2))$$

2.1 The Silicon Tracker

At the heart of CMS is one of the world’s largest silicon detectors: the silicon tracker. The main goal of the silicon tracker is not to capture outgoing particles but to very precisely measure the hits from the charged particles as they pass through it. The tracker also assists in vertex identification, differentiating between primary and secondary vertices, the latter of which often comes from B meson decays. When multiple pp collisions occur within the same BX (pile up), the tracker distinguishes between proton collisions with a resolution of about $100 \mu\text{m}$ longitudinally and $50 \mu\text{m}$ transverse to the beam pipe. This is crucial to resolve which outgoing particles came from which pp vertex.

The tracker consists of two types of pure silicon detectors: the pixel detector and the strip detector, each of which is described in detail below.

2.1.1 The Pixel Detector

The innermost part of the silicon tracker is the pixel detector, which is the closest subdetector to the interaction point. The pixel detector is composed of 66 million silicon “pixels”, as shown in Fig. 2-5 (Left, pink). A single pixel is $100 \mu\text{m} \times 150 \mu\text{m}$ and, collectively, they cover a sensitive area of 1.9 m^2 . Because it sits only 8 cm away from the beam pipe, the pixel detector receives the highest particle flux than any other subdetector: around 10 million particles per cm^2 per second.

The pixel detector is made of three cylindrical layers and two endcaps that surround the beam pipe. In total, the pixel detector has around 6,000 connections (channels) per cm^2 .

After the LHC Run 1 was completed, the accelerator received luminosity upgrades during the 2013-2014 long shutdown period. To handle these higher luminosities, the pixel detector was replaced by the CMS Phase-1 pixel detector during the LHC technical stop in 2016-2017. The upgrades outfitted the detector with four barrel layers and three endcap disks per side, which allowed

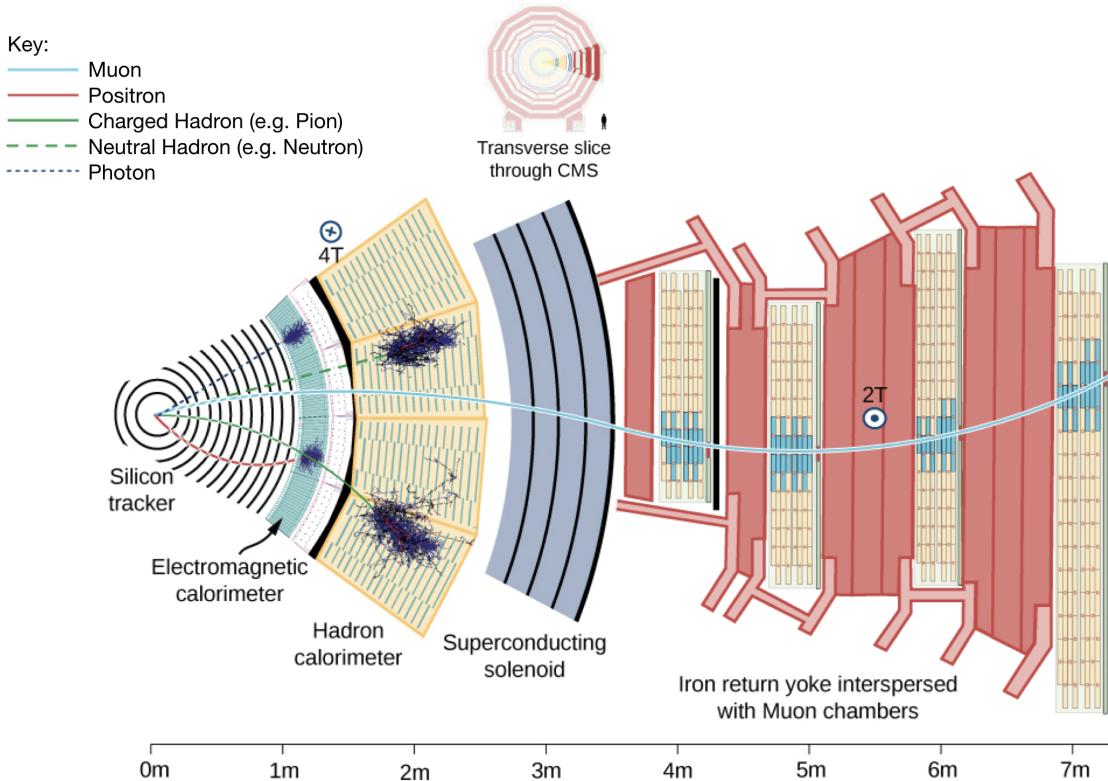


Figure 2-4. A transverse view of CMS showing the “filtration process” as different particles pass through different subdetectors. A positron (solid red line) curves due to the presence of the magnetic field and gets stopped in the ECAL, creating an EM shower. A photon (blue dashed line) does not get detected at all by the Silicon Tracker, since it has no electric charge. It continues through to the ECAL and makes a shower here, like the positron. Charged hadrons (solid green line) will show curved tracks from the Silicon Tracker, may leave some trace in the ECAL, but primarily get stopped by the HCAL creating hadronic showers. Neutral hadrons (dashed green line) do not interact with the tracker, and only undergo EM showers a little in the ECAL, but show most energy deposits in the HCAL. Muons (solid blue line) are detected by the Silicon Tracker and then mostly pass through the other subdetectors without interacting until they finally reach the Muon System. Using the Lorentz force law and knowing which direction the magnetic field is pointing, one can deduce the sign of the charge of the particle. Based on the radius of curvature from the trajectory, one can then calculate the momentum and energy of the particle.

for particle detection up to $|\eta| < 2.5$. The overall mass of the pixel detector decreased and granted the detector with better tracking capability.

2.1.2 The Strip Detector

The outer part of the silicon tracker is called the strip detector, which has 10 million detector strips spread across 10 cylindrical layers. The first 4 layers belong to the tracker inner barrel (TIB) and the remaining 6 layers belong to the tracker outer barrel (TOB), Fig. 2-5 (Left, green and blue, respectively). Both the TIB and TOB have two endcaps associated with them, the TID and TEC, respectively. Accounting for all of its components, the strip detector is sensitive to 200 m^2 . Fig. 2-6 gives a clearly-labelled transverse illustration of the pixel and strip detectors.

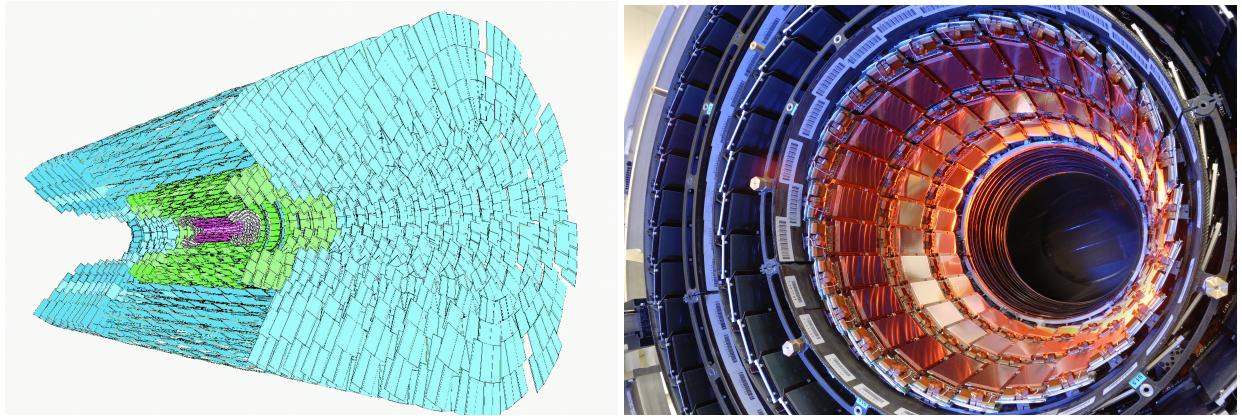


Figure 2-5. (Left) A simulation of the silicon tracker, showing the 3 cylindrical layers of the pixel detector (pink), 4 layers of the TIB (green), and the 6 layers of the TOB (blue) of the strip detector. The endcap components are also shown. (Right) A picture of the real silicon tracker at the center of CMS.

2.2 The Calorimeters

2.2.1 Electromagnetic Calorimeter

What is it? Particles that pass through the silicon tracker 2.1 encounter the electromagnetic calorimeter (ECAL). Those particles which interact electromagnetically but not strongly, mostly photons and electrons, are typically absorbed by the ECAL. The particle's energy is then transferred to the ECAL in the form of an electromagnetic (EM) shower. The size and shape of the EM shower provide information about the particle's energy and trajectory. Since the Higgs boson can decay into two photons, it was essential that the ECAL was able to detect this decay mode.

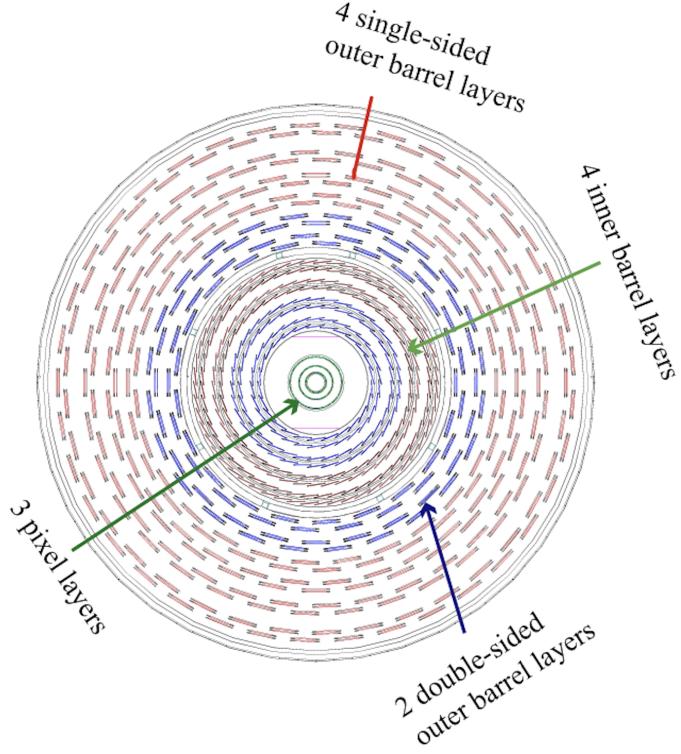


Figure 2-6. A transverse view of the silicon pixel and strip detectors, explicitly labelling the different layers involved.

Structure: The ECAL is a hermetic, cylindrical, homogeneous sub-detector that consists of a barrel (EB), two endcaps (EE), and a preshower detector in front of each endcap (Figure 2-7, Left). The EB covers $|\eta| < 1.479$ while the EE covers $1.479 < |\eta| < 3.0$. The entire subdetector is composed of transparent lead tungstate (PbWO_4) crystals that point axially towards the center of CMS (the interaction point). The transparent crystals, one of which is shown in Fig. 2-8 (Left), have a high density (8.28 g/cm^3) which provides the ECAL with radiation resistance and a short radiation length ($X_0 = 0.89 \text{ cm}$). Because so many crystals are used (61,200 crystals in the EB and 7,324 in the EE), the ECAL has excellent energy resolution and fine granularity. Each endcap is composed of two “Dee”s, one of which is shown in Figure 2-7 (Right). A single Dee carries 3,662 crystals. Crystals in the barrel are tapered, having front face dimensions $2.2 \times 2.2 \text{ cm}^2$, back face dimensions $2.6 \times 2.6 \text{ cm}^2$, and are 23.0 cm long ($25.8 X_0$). Crystals in the endcaps are also tapered, with front face dimensions $2.862 \times 2.862 \text{ cm}^2$, back face dimensions $3.0 \times 3.0 \text{ cm}^2$, and are 22.0 cm long ($24.7 X_0$). This gives a single crystal from the barrel a volume of approximately 132.5

cm^3 (mL), about the volume of a small cup of coffee, yet it weighs 1.5 Kg. (REF:PDG). REF:PDG Particle Data Group collaboration, S. Eidelman et al., *Review of particle physics*, *Phys. Lett. B* **592** (2004) 1

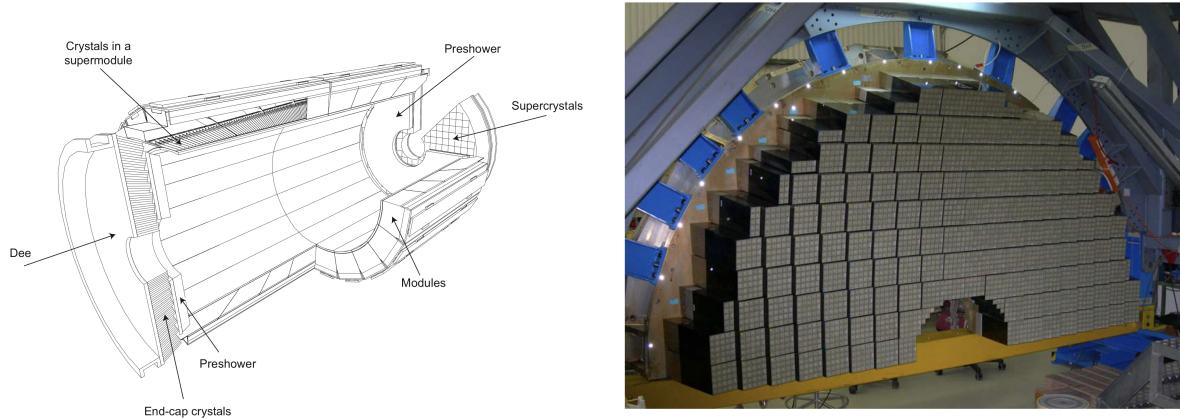


Figure 2-7. (Left) Cross sectional view of the electromagnetic calorimeter of CMS. (Right) One of the Dees which comprise the EE. Each square of 5×5 crystals constitutes a “super-crystal”. Figure taken from Ref.REFERENCE JINST

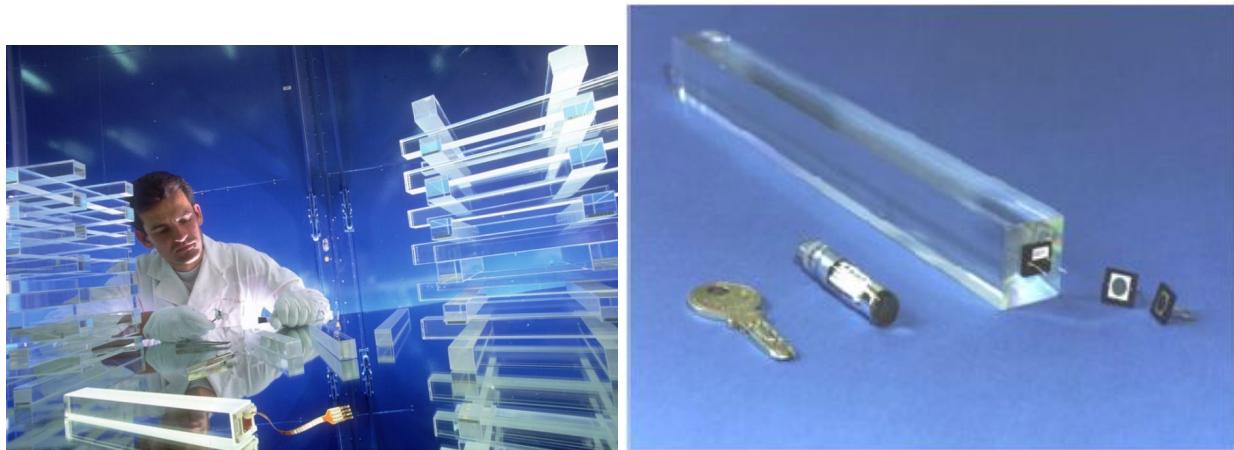


Figure 2-8. (Left) ECAL crystals made from PbWO₄ are grown in a lab. (Right) Although made mostly of metal, ECAL crystals are transparent and have a photomultiplier detector attached at the end.

Physics: When electrons or photons pass through the ECAL, they create an EM shower. Electrons radiate more photons as they accelerate around PbWO₄ nuclei, in a process called *bremssstrahlung*. Meanwhile, near the presence of a nucleus, high-energy photons pair produce into e^+e^- . This cycle of electron and photon production disperses the initial particle energy into a spray

of lower- and lower-energy particles; an EM shower (REFERENCE EM SHOWER FIG).

SHOW PICTURE OF EM SHOWER.

The ECAL crystals then scintillate (emits photons) in proportion to the amount of energy deposited by the interacting particle. The scintillator photons are detected by avalanche photodiodes on the back of each barrel crystal or by vacuum phototriodes in the endcap crystals (Fig. 2-8, Right). Conveniently after 1 bunch crossing (25 ns), Approximately 80% of the scintillated light is emitted.

An energy deposit in the ECAL could come from either an electron or a photon. In order to tell the difference, information from the silicon tracker is used. Charged particles, like electrons, will leave hits in the tracker and follow a curved path, whereas photons are electrically neutral and thus will not show any signs within the silicon tracker. So long as the tracker and ECAL communicate effectively with each other, then they help distinguish between electrons and photons. Charged hadrons interact only minimally with the ECAL, instead continuing on to the Hadron Calorimeter. Neutral hadrons can be detected by the ECAL preshower near the ECAL endcaps which helps distinguish a single photon from π^0 mesons as they decay into two photons with a narrow opening angle, making it look as if the two photons are a single photon. The preshower detector allows CMS to distinguish between low-energy diphoton pairs and single high-energy photons.

NEED SMOOTH TRANSITION INTO HCAL. What about those hadrons? They got through the ECAL... To detect hadrons effectively, we need a Hadron Calorimeter.

2.2.2 Hadron Calorimeter

What is it? The particles that survive the ECAL, typically only muons and hadrons, then enter the hadron calorimeter (HCAL). Its primary purpose is to absorb the hadronic matter emerging from the interaction point and measure the corresponding jet energies. The absorbed jets cause the HCAL to scintillate photons which are then converted into electrical signals. These signals are used to deduce the original jet energies and any missing transverse energy (E_T^{miss}) from the event.

Structure: Dissimilar to the ECAL (subsec. 2.2.1) in material composition but similar in shape, the HCAL is a brass cylindrical scintillator. Although it has a barrel (HB) and two endcaps

(HE), it has two more detectors than the ECAL: the outer calorimeter (HO) and the forward calorimeter (HF). The HB spans the pseudorapidity range $|\eta| < 1.3$, the HE spans $1.3 < |\eta| < 3$, and the HF spans $3 < |\eta| < 5.2$, as shown in Figure 2-9. With a thickness of over 1m, the HB is sandwiched between the barrels of the ECAL and the solenoid (subsec. 2.3) at radial values $r = 1.77$ m and $r = 2.95$ m, respectively. Because the HB and HE are located within the solenoid’s strong magnetic field of 3.8 T, they both were both constructed out of a non-magnetic absorber called *C26000 cartridge brass*. This absorber has a density of 8.53 g/cm^3 and an interaction length (λ_I) of 16.42 cm. The thickness of the HB increases as $1/\sin\theta$ so that at $|\eta| = 0(1.3)$ the absorber thickness is $5.82(10.6) \lambda_I$. The HB is composed of two half-barrels, where each half-barrel is built from 18 identical azimuthal wedges and each wedge spans 20° . Each wedge is divided into four ϕ segments so that a single ϕ segment spans $\Delta\phi = 0.087$.

Since the volume available to the HCAL is so limited, and in order to stop any particles that might traverse the entire HCAL and solenoid, the HO (the “tail catcher”) is situated outside the barrel of the solenoid. The HF is located 11.2 m from the interaction point.

All tiles within a single ϕ segment are grouped together into a single tray unit. The scintillator is also segmented into 16 η sectors, the first(last) of which is located at $|\eta| = 0(1.3)$. This way each tile covers $(\Delta\eta, \Delta\phi) = (0.087, 0.087)$. Each layer has 108 trays.

Physics: Since hadrons are the only particles to interact via the strong force, the HCAL is designed to have a high nuclear density. This ensures ample opportunity for hadrons to radiate gluons and convert with the Similar to the ECAL, the HCAL will scintillate in proportion to the amount of energy of the captured particle. The incoming hadrons will *hadronize* (i.e., produce a hadronic shower), generating jets of quarks and gluons which are bound in various ways forming protons, neutrons, pions, kaons, etc. Interestingly, the HCAL is made using over a million old, brass shell casings from the Russian Navy back from World War II.

About 34% of the particles produced from LHC pp collisions enter the HE region, so the HE was built to handle high rates (MHz).

The entire HCAL utilizes approximately 70,000 plastic scintillator tiles. The active material

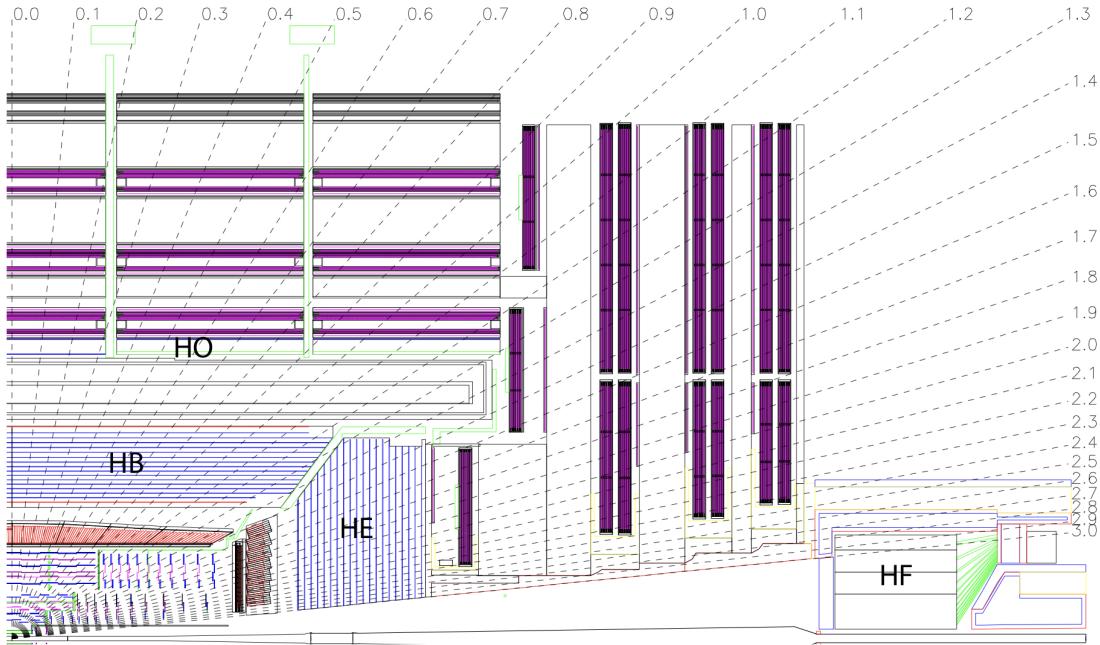


Figure 2-9. A cross-sectional quadrant of CMS showing the locations of the HCAL components: the barrel (HB), outer (HO), endcap (HE), and forward (HF) detectors.

in the HB is 3.7-mm-thick Kuraray SCSN81 plastic scintillator, selected for its radiation hardness and long-term stability. Hadron showers \rightarrow tiles scintillate \rightarrow scintillated photons are collected by 0.94-mm-diameter green double-cladded wavelength shifting (WLS) fibers (Kuraray Y-11), which carry the light to hybrid photodiodes (HPD).

2.3 The Solenoid and the Steel Return Yoke

The Compact Muon *Solenoid* sports one of the world's most energetic solenoids which is paramount to the success of CMS. Particles that exit the HCAL (subsec. 2.2.2) arrive at the cylindrical magnet which is 12.5 m in length, has a bore diameter of 6 m (6.3 m when cold), and generates a uniform 3.8 T magnetic field parallel to the beam line. To produce such a large and uniform magnetic field inside the approximately 360 m^3 volume (Fig. 2-10), an 18,000 amp current travels through the 4-layer, superconducting, NbTi coils. This magnetic field is 100,000 times stronger than Earth field at the surface, storing a massive 2.6 GJ of energy—approximately the kinetic energy of an Airbus A320 in flight. The magnet has such a

large stored-energy-to-cold-mass ratio (11.6 KJ/Kg) that it experiences a physical deformation of 0.15% while energizing the field.

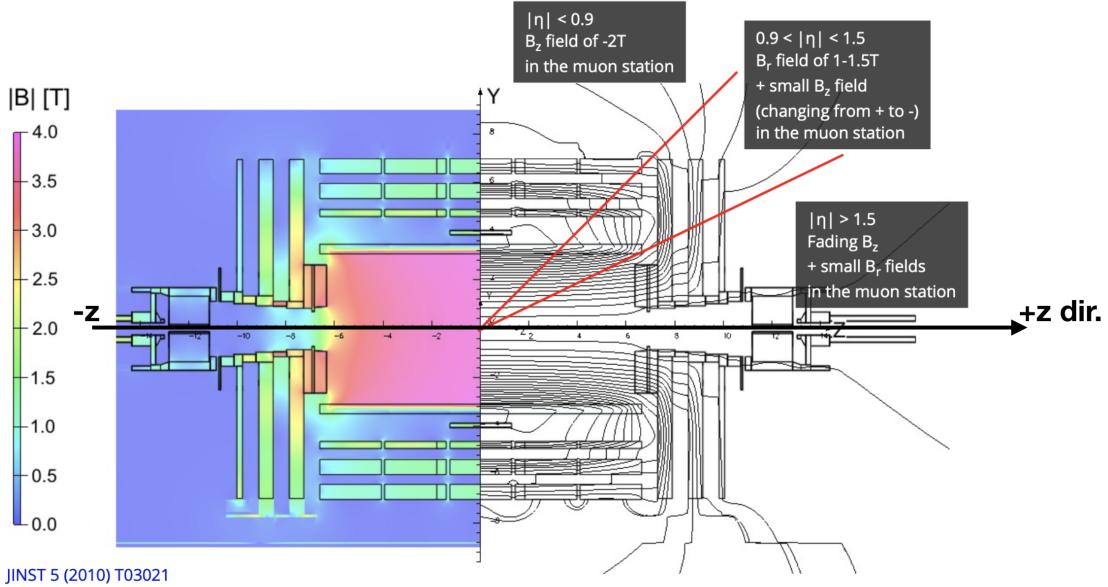


Figure 2-10. A longitudinal cross section of CMS showing the values of the magnetic field over the volume of CMS and various field lines. The magnetic field reaches its maximum of 3.8 T in the center of the detector.

As charged particles travel through any magnetic field, they experience a magnetic (Lorentz) force perpendicular to their direction of travel. The Lorentz force (\vec{F}_B) exerted on a particle with charge q depends on the particle's velocity (\vec{v}) and the strength of the magnetic field (\vec{B}), given by

$$\vec{F}_B = q\vec{v} \times \vec{B}$$

Since the force is necessarily perpendicular to the velocity, the resulting trajectory is a helix. Projecting the helix on the x - y plane (since the magnetic field points in the $+z$ direction) allows the particle tracks to typically be separated from one another. Each track has a corresponding radius of curvature (R) which relates to its transverse momentum (p_T) through

$$p_T = qBR.$$

The relative change in p_T (i.e. the momentum resolution) is given by

$$\frac{\delta p_T}{p_T} \propto \frac{p_T}{BL^2}. \quad (2-1)$$

Steel Return Yoke: Most of the mass of CMS comes from the *steel return yoke* which helps to redirect the magnetic field back on itself. The yoke system constitutes 10,000 tonnes, which is 89% of the total mass of CMS. It is comprised of 5 wheels and 2 endcaps

2.4 The Muon System

Although it is the farthest system from the interaction point, the muon system is one of the most important within the Compact *Muon* Solenoid detector. Of the particles emerging from the interaction point, electrons and photons are absorbed by the ECAL (subsec. 2.2.1), hadronic matter is absorbed by the HCAL (subsec. 2.2.2), but muons are not stopped due to their relatively heavy mass (105.7 MeV) for a lepton. The only *detectable* particles remaining at this point are muons, which interestingly will travel way outside of CMS before decaying, upwards of 100s of kilometers before decaying to an electron and neutrino (neutrinos are the only particles which CMS can't explicitly detect).

The main purpose of the Muon System is to precisely determine the position and timing of muons. Similar to the Silicon Tracker, the Muon System doesn't try to capture the muons passing through it; instead it just tracks their positions. The Muon System is comprised of three kinds of gaseous detectors:

1. **Drift Tubes** (DTs) found in the barrel.
2. **Resistive Plate Chambers** (RPCs) found in both the barrel and endcap.
3. **Cathode Strip Chambers** (CSCs) found only in the endcap.

Each of these technologies is constructed differently and was designed with a specific purpose.

This concludes the overall design and purpose of the subdetectors that make up CMS. Since I have had hands-on experience working on CSCs, I will discuss the CSC components and how it works in more detail in the subsection below.

2.4.1 Let Me See These CSCs

A cathode strip chambers (CSC) is a gaseous detector which specializes in muon detection.

Quick Mention: The University of Florida has been one of the main contributors to the CSC system and was home to one of the testing and assembly facilities before shipping the CSCs off to CERN. The CSCs are found only on the endcaps of CMS and each endcap holds 270 CSCs (Fig 2-11). Each CSC cost about \$100,000 to make, so very quickly this becomes an expensive

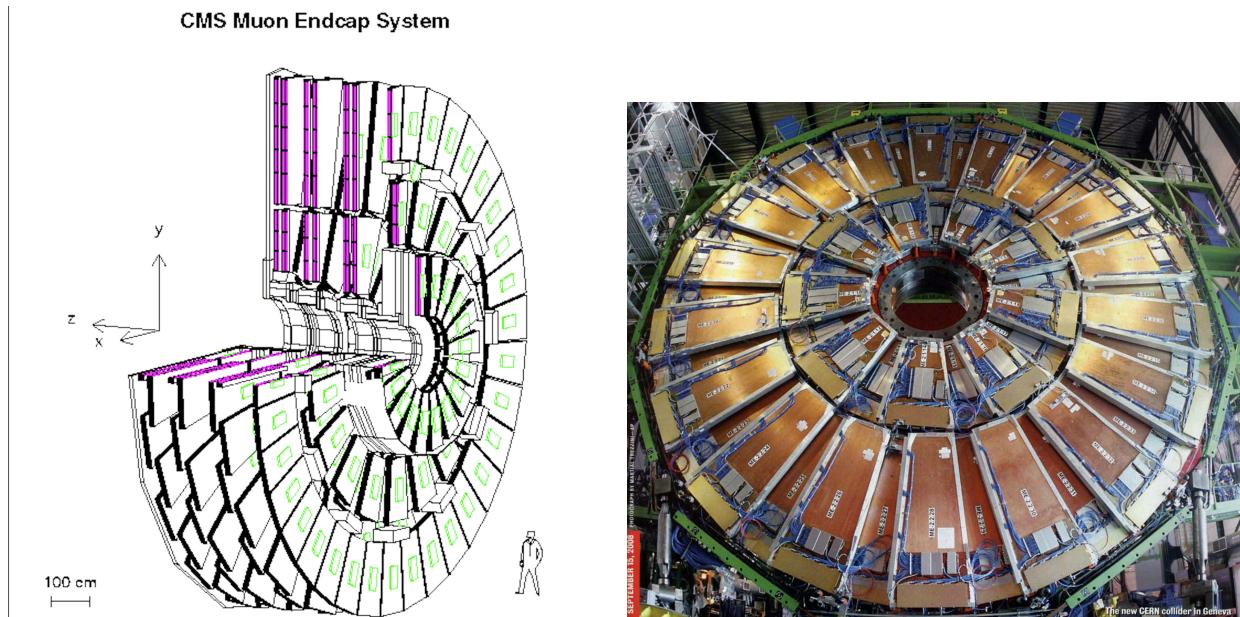


Figure 2-11. (Left) A cut out view of the ME+ endcap, simulated. Also shown is the coordinate system that CMS uses. (Right) The actual ME-2 disk is shown, revealing its ME-2/1 and ME-2/2 rings of CSCs.

project. They are trapezoidal in shape and are composed of 6 layers filled with gas. The gas surrounds wires and strips which are put under 3,600 V to aid in muon detection as explained below (Fig. 2-12). The gaseous mixture of Ar : CO₂ : CF₄ in the ratio of 5 : 4 : 1 has been specially designed to maximize the lifetime of the CSC as it endures radiation damage over the years. In each layer, the gas mixture surrounds approximately 80 copper strips, each about 1 cm wide that span radially away from the IP. Also inside the layers are over 1,000 gold-plated tungsten wires, which run azimuthally in the CMS coordinate system. When the strips and wires detect muons they provide an (x,y) coordinate system to track the muon. As the muon passes through the remaining

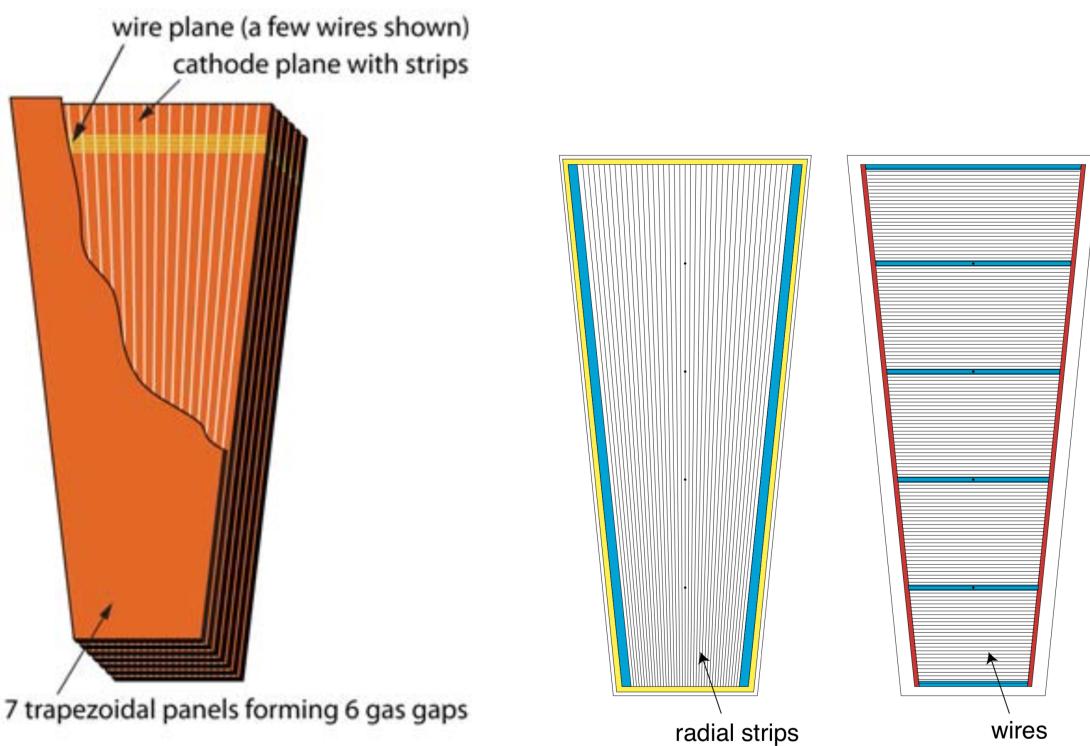


Figure 2-12. (Left) A CSC with its top layer exposed. You can see very thin gold-plated tungsten wires which actually span the entire width of the CSC. Thicker vertical strips run along the length. (Right) More detail showing the radial strips and the horizontal wires. Also shown is the 5 segments of a CSC.

layers of the CSC, this provides a z coordinate as well, giving the Muon System the ability to “see” the full muon trajectory.

Labelling the CSCs: The two endcaps are labelled as “ME+” and “ME-”, depending on in which z-direction they sit. Since they are structurally the same, let’s focus on the ME+ endcap for a moment. The ME+ endcap has four disks, where ME+1 is the first disk, the one closest to the IP, and ME+4 is the fourth and farthest away. Similarly for the ME- endcap. Then, within each disk, there are either two or three “rings” of CSCs, as shown in Fig 2-13 (green). These rings are labelled like ME+2/1, which would indicate the second disk and the first (innermost) ring, radially closest to the IP. All rings contain 36 CSCs, except for ME $\pm X/1$, for $X = 2,3,4$, which contain only 18 CSCs. Finally, the CSCs are given one, last number to label them on the ring: the CSC that sits along the positive x-axis in CMS’s coordinate system is given the number “01”, e.g. ME+4/2/01. The CSCs are then numbered incrementally following the positive azimuthal direction.

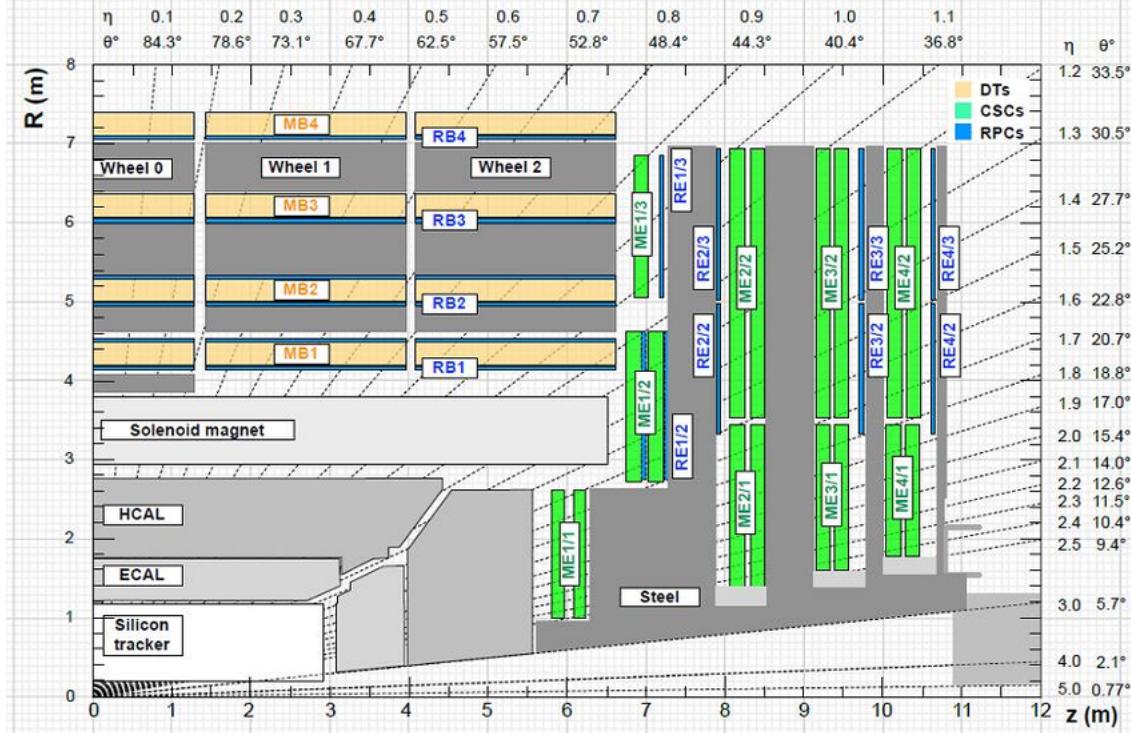


Figure 2-13. Longitudinal cross section of CMS, showing the different pseudorapidity values (η) and also the different subdetector regions.

Detecting Muons: When a muon passes through a layer of a CSC, it has the chance to ionize

an Ar atom (Fig. 2-14). Since the wires are under high voltage (3,600 V), the ionized electron accelerates towards the positively-charged wire, and in doing so it ionizes many Ar atoms which are along its path. Starting from just a single electron, the multiplicity can go as high as 100,000 ionized electrons, thereby creating what is known as an electron avalanche. This phenomenon is called “gas gain”. The electrons travel onto the wire and become an electrical signal which then

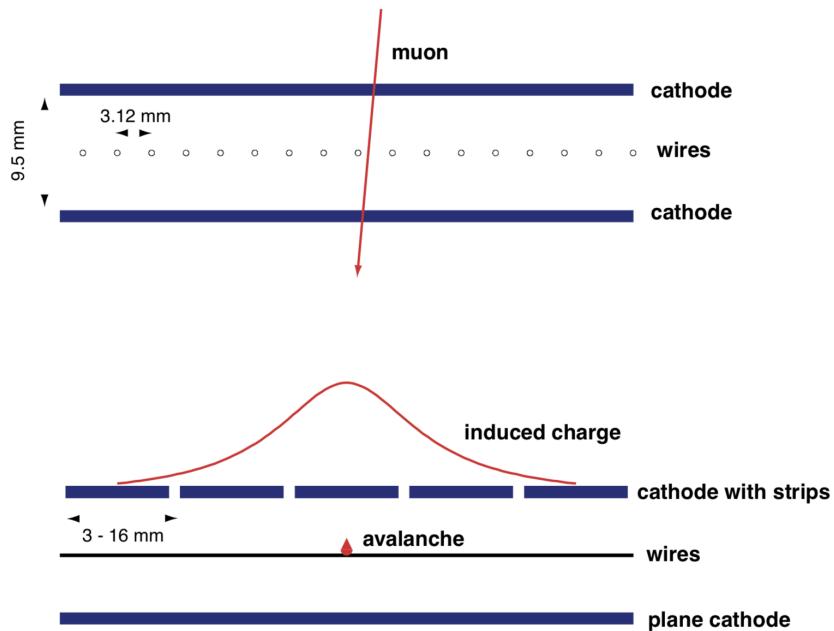


Figure 2-14. A muon passes through one of the gaseous layers of the CSC, ionizing the gas mixture and inducing a charge on the wires and strips.

gets sent to the anode front-end boards (AFEBS) for further signal processing. The ionized Ar^+ will similarly distribute a charge signal on the negative strips. This cluster of charge is much more widely spread over the strips compared to the charge on the wires. Therefore, comparator logic is implemented to narrow down the precision to the order of $100 \mu\text{m}$ by using half-strip information (Fig. 2-15).

The muon will continue passing through the next 5 layers, repeating the process of ionizing the gas mixture, and depositing an electrical signal on the wires. The wires and strips provide (x,y) -coordinates, and as the muon passes through the CSC, the other layers provide a z -coordinate,

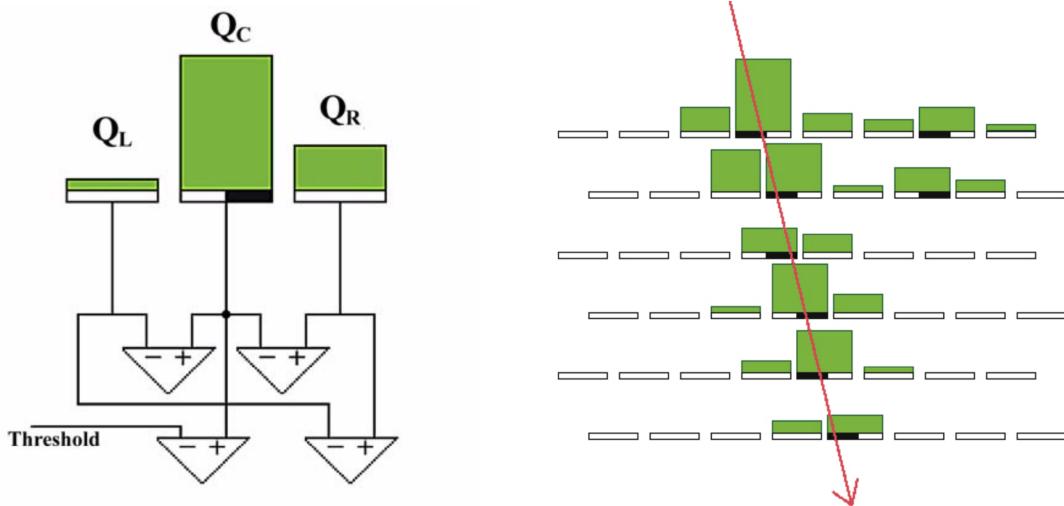


Figure 2-15. (Left) Comparators are used to compare neighboring strip cluster charge to determine on which half-strip the peak charge resided. (Right) A muon passes through all six layers of a CSC inducing charge on various half-strips.

revealing the path of the muon. Depending on how many hits were recorded by the CSC will determine if a muon event was significant enough to be registered as a real muon. If so, then its precise positions on the wires and strips will be read out by the Data Acquisition (DAQ) system and be stored for further data analysis.

2.4.2 Drift Tube Chambers

2.4.3 Cathode Strip Chambers

2.4.4 Resistive Plate Chambers

CHAPTER 3 SUMMARY

words.